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AN APPROXIMATE SOLUTION FOR THE RESPONSE OF A SPHERE IN A TACTI--ETC(U)

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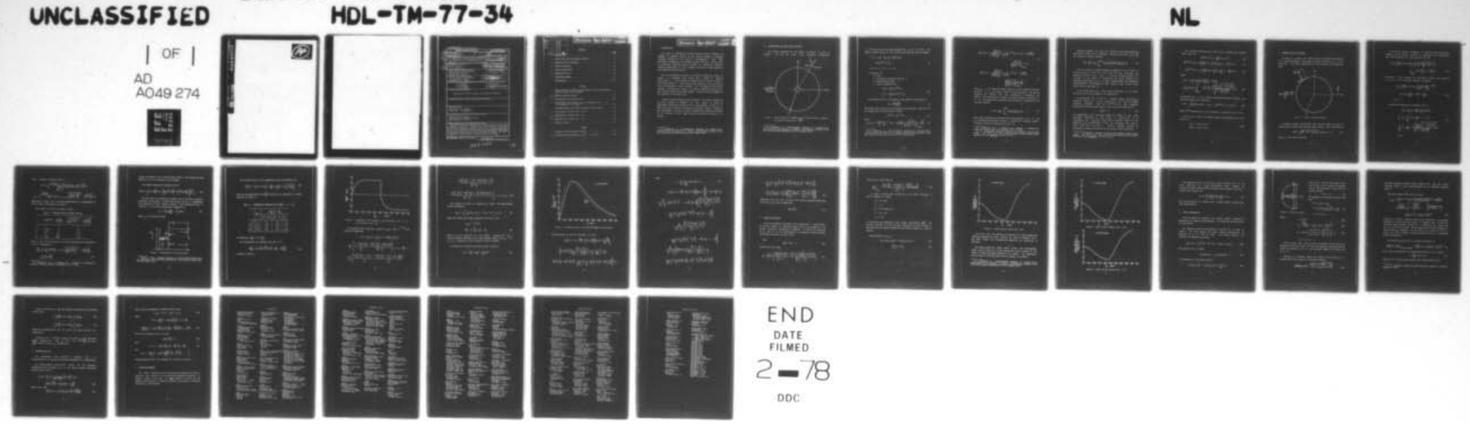

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Bombardt (1975) has discussed an early time model for the electromagnetic response of a sphere over a guard plane in the presence of source and conduction currents in the air. In this report the formal field solutions from this model are approximately evaluated via contour integration of inverse Laplace transforms. The resulting scattered radial electric field is used to estimate the electromagnetic pulse response of a sphere-mounted antenna.

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1. INTRODUCTION

One class of problems of current military interest concerns the response of antennas mounted on the exterior surface of metallic equipment shelters to the tactical electromagnetic pulse (EMP) environment created by a near-surface nuclear detonation. With the hope of ultimately obtaining models suitable for engineering purposes, analytic formulations of such problems are posed in ideal geometries with simplified problem physics.

One such formulation consists of a perfectly conducting sphere of radius a, in unbounded space filled with a medium of constant conductivity σ, in the presence of Compton electron flux of velocity v and current density J_c. The source-current density is curl-free and the total electromagnetic current density (in the absence of the sphere) vanishes. The sphere is treated as ideally gamma-thin; that is, for each electron entering the sphere another electron leaves the sphere in the direction of the photon flux.

A formal, frequency-domain series solution to the latter formulation has been obtained by Bombardt.[1] In this report, we obtain an approximate time-domain solution for the electromagnetic fields on or about the sphere by contour integration of inverse Laplace transforms. The approximate solutions are used to perform some tentative estimates of the coupling of the radial electric field near the sphere to an antenna.

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[1]*J. N. Bombardt, Jr., Electromagnetic Response of a Sphere Over a Ground Plane in the Presence of Source and Conduction Currents in the Air, Harry Diamond Laboratories TR-1716 (October 1975).*

2. SPHERE MODEL AND APPROXIMATE SOLUTION

The problem geometry[1] for the sphere of radius a is shown in figure 1. We use mks units with free-space permittivity

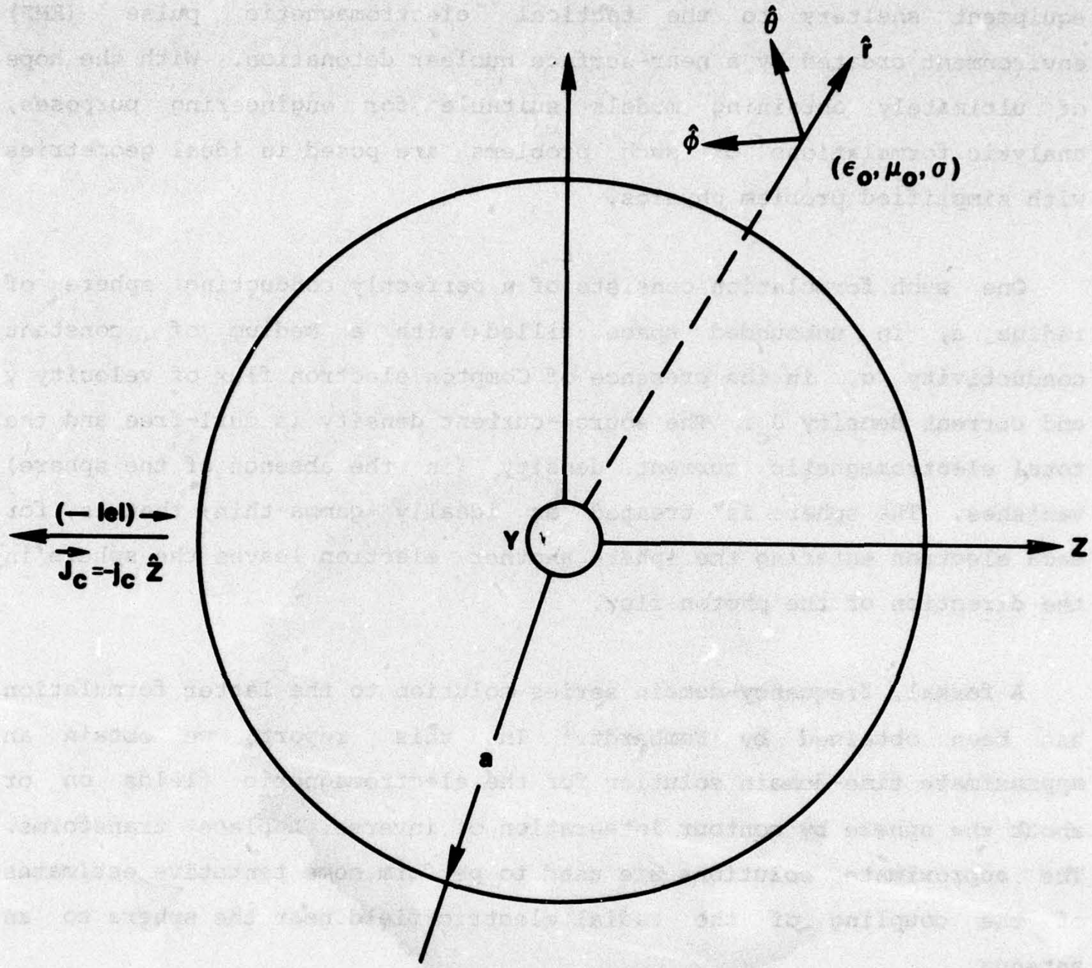

Figure 1. Sphere exposed to Compton current density--A/m^2 in presence of constant conductivity $\sigma \frac{\text{mhos}}{\text{m}}$.

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[1] *J. N. Bombardt, Jr., Electromagnetic Response of a Sphere Over a Ground Plane in the Presence of Source and Conduction Currents in the Air, Harry Diamond Laboratories TR-1716 (October 1975).*

$\varepsilon_o = 10^{-9}/36\pi$ F/m and free-space permeability $\mu_o = 4\pi \times 10^{-7}$ H/m. The Compton current density is, with explicit sign for the electron charge,

$$\vec{J}_c = -j_c\left(t - \frac{z}{v}\right) u \left(t - \frac{z}{v}\right) \vec{z} \text{ A/m}^2$$

$$= \tilde{f}(\omega)e^{i\beta z}, \ \beta = \frac{\omega}{v} \tag{1}$$

$$u(t) = 0 \ (t < 0); = 1 \ (t > 0) .$$

In equation (1),

t = time,

z = horizontal coordinate (see fig. 1),

u = Heaviside unit step,

ω = radian frequency, and

$$-\tilde{f}(\omega) = \int_{-\infty}^{\infty} j_c(t)e^{i\omega t} \, dt$$

$$-j_c(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \tilde{f}(\omega)e^{-i\omega t} \, d\omega . \tag{2}$$

The electric field in the medium in the absence of the sphere is

$$E_z^i = \frac{-\tilde{f}(\omega)e^{i\beta z}}{\sigma - i\omega\varepsilon_o} . \tag{3}$$

The formal series solution of the boundary value problem[1] yields the sum of incident and scattered electric fields:

$$\vec{E}^{\text{ total}} = \vec{E}^{i} + \vec{E}^{s} , \tag{4}$$

where

$$\tilde{H}_\phi(r,\theta,\omega) = \frac{-\tilde{f}(\omega)}{\frac{\omega}{v}} \sum_{n=1} i^{n-1} (2n + 1) j_n\left(\frac{\omega a}{v}\right) \frac{h_n^{(1)}(kr)}{\frac{d}{du}\left[u h_n^{(1)}(u)\right]_{u=ka}} \frac{\partial P_n}{\partial \theta} \tag{5}$$

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[1] *J. N. Bombardt, Jr., Electromagnetic Response of a Sphere Over a Ground Plane in the Presence of Source and Conduction Currents in the Air, Harry Diamond Laboratories TR-1716 (October 1975).*

$$\tilde{E}^{s}_{r}(r,\theta,\omega) = \frac{\left(\frac{a}{r}\right)\tilde{f}(\omega)}{\varepsilon_o\left(\frac{\omega a}{v}\right)\left(\frac{\sigma}{\varepsilon_o} - i\omega\right)} \sum_{n=1} i^{n-1} n(n+1)(2n+1) j_n\left(\frac{\omega a}{v}\right) \cdot \frac{h_n^{(1)}(kr)}{\frac{d}{du}\left[u h_n^{(1)}(u)\right]_{u=ka}} P_n \tag{6}$$

$$\tilde{E}^{s}_{\theta}(r,\theta,\omega) = \frac{\left(\frac{a}{r}\right)\tilde{f}(\omega)}{\varepsilon_o\left(\frac{\omega a}{v}\right)\left(\frac{\sigma}{\varepsilon_o} - i\omega\right)} \sum_{n=1} i^{n-1}(2n+1) j_n\left(\frac{\omega a}{v}\right) \cdot \frac{\frac{d}{du}\left[u h_n^{(1)}(u)\right]_{u=kr}}{\frac{d}{du}\left[u h_n^{(1)}(u)\right]_{u=ka}} \frac{\partial P_n}{\partial \theta} \tag{7}$$

where j_n is the spherical Bessel function, P_n the Legendre polynomial and $h_n^{(1)} = j_n + iy_n$ the Hankel function of the first kind. All special functions are defined with the conventions of Abramowitz and Stegun.[2] For convenience, we convert the Fourier forms in equations (5) to (7) to Laplace form and perform (term by term) an evaluation of the inversion integral

$$g(t) = \frac{1}{2\pi i} \int_{d-i\infty}^{d+i\infty} \exp\left(tz_o\right)\tilde{g}\left(z_o\right)\, dz_o \tag{8}$$

where $g\left(z_o\right)$ represents the desired field from equations (5) to (7) and z_o is the Laplace transform variable, s, regarded as a complex variable. A Bromwich contour[3] is employed (see sect. 5).

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[2] *M. Abramowitz and I. A. Stegun, eds., Handbook of Mathematical Functions, National Bureau of Standards, AMS 55 (1965).*

[3] *F. B. Hildebrand, Advanced Calculus for Engineers, Prentice Hall (1949). (We start with the Fourier integral theorem having complex exponential signs opposite to 87(a), p 601).*

Formally, equation (8) does not converge on the large semicircle because of a factor in the integrand modulus arising from $j_n\left(iz_o \frac{a}{v}\right)$. We, therefore, actually evaluate

$$g\left(t + \frac{a}{v}\right) = \frac{1}{2\pi i} \int_{d-i\infty}^{d+i\infty} \exp\left(tz_o\right) \left[\exp\left(\frac{a}{v} z_o\right)\tilde{g}\left(z_o\right)\right] dz_o \, . \tag{9}$$

Term by term, the right-hand sides of equations (5) to (7) have no poles (see sect. 5), for $\sigma \neq 0$, other than the pole introduced into equations (6) and (7) by $\sigma - i\omega\varepsilon_o$. In order to evaluate equation (9), we resort to the ansatz of calculating for the H_ϕ evaluation, an integrand multiplied by $1/(s + \varepsilon)$, with ε infinitesimal, then subsequent differentiation. The operand is a step function which yields a Dirac delta function (see sect. 5).

If we use the pole at $z_o = -\sigma/\varepsilon_o$ for the evaluation of E_r^s and E_θ^s, the factor $(a/v)(\sigma/\varepsilon_o)$ appears in our expressions.

We can evaluate E_r^s and E_θ^s by a similar ansatz used for H_ϕ by extracting $\tilde{f}(s)/[\varepsilon_o(s + \sigma/\varepsilon_o)]$ rather than $\tilde{f}(s)$ from the Laplace inversion integrand. With $f(0) = E^{(inc)}(0) = 0$, the subsequent convolutions yield the same result as the σ/ε_o pole evaluations for

$$\frac{\sigma}{\varepsilon_o} \frac{a}{v} << 1 \, . \tag{10}$$

The approximate field solutions should be subject to the usual skin-depth restriction we give below. In equation (9), it is interesting that $(\sigma/\varepsilon_o)(a/v)$ enters the n=1 electric field via the factor $\left(1 + \left[(\sigma/\varepsilon_o)(a/v)\right]^2/10\right)$ in which the difference from unity is small, even for $(\sigma/\varepsilon_o)(a/v) \sim 1$. Lerch's Theorem[3] assures the uniqueness of equation (15) below in the electric field evaluations.

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[3]*F. B. Hildebrand, Advanced Calculus for Engineers, Prentice Hall (1949). (We start with the Fourier integral theorem having complex exponential signs opposite to 87(a), p 601).*

The resulting solutions for a step in $\tilde{f}(\omega)$, including the electron charge sign, are

$$H_\phi^{step}(r,\theta,t) \simeq a\left(\frac{a}{r}\right)^2 D(t)\ \sin\theta \tag{11}$$

$$E_r^{s\ step}(r,\theta,t) \simeq \frac{2}{\varepsilon_o}\left(\frac{a}{r}\right)^3 \cos\theta \int_o^t \exp\left[-\frac{\sigma}{\varepsilon_o}(t-\tau)\right] D(\tau)\ d\tau \tag{12}$$

$$E_\theta^{s\ step}(r,\theta,t) \simeq \frac{1}{\varepsilon_o}\left(\frac{a}{r}\right)^3 \sin\theta \int_o^t \exp -\left[\frac{\sigma}{\varepsilon_o}(t-\tau)\right] D(\tau)\ d\tau \tag{13}$$

where

$$D(t) = \exp\left[-\frac{\sigma}{2\varepsilon_o}\left(\frac{r-a}{c}\right)\right] u\left(t - \frac{r-a}{c}\right)$$

$$+ \frac{\sigma}{2\varepsilon_o}\left(\frac{r-a}{c}\right) \int_{\frac{r-a}{c}}^{t} \exp\left[-\frac{\sigma}{2\varepsilon_o}\tau'\right] \frac{I_1\left[\frac{\sigma}{2\varepsilon_o}\sqrt{\tau'^2 - \left(\frac{r-a}{c}\right)^2}\right]}{\sqrt{\tau'^2 - \left(\frac{r-a}{c}\right)^2}}\, d\tau' \tag{14}$$

In equation (14), I_1 is an integer order modified Bessel function. The desired responses are, therefore,

$$g(t) = \int_o^t \frac{\partial}{\partial(t-\tau)}\left[j_c(t-\tau)u(t-\tau)\right] g^{step}(\tau)\ d\tau,\quad j_c(0) = 0 \tag{15}$$

where g^{step} represents any of the functions in equations (11) to (13).

At r=a, the *H* field and surface current from equations (11), (14), and (15) is

$$H_\phi(t) \simeq a j_c(t) \sin\theta$$

$$K_\theta(t) \simeq -a j_c(t) \sin\theta \quad . \tag{15'}$$

3. ANTENNA COUPLING ESTIMATES

We desire to estimate the short-circuit base-current contribution for an antenna mounted on the sphere as shown in figure 2, due to the field E_r^s. The direct coupling of E_i to the antenna is not considered here.

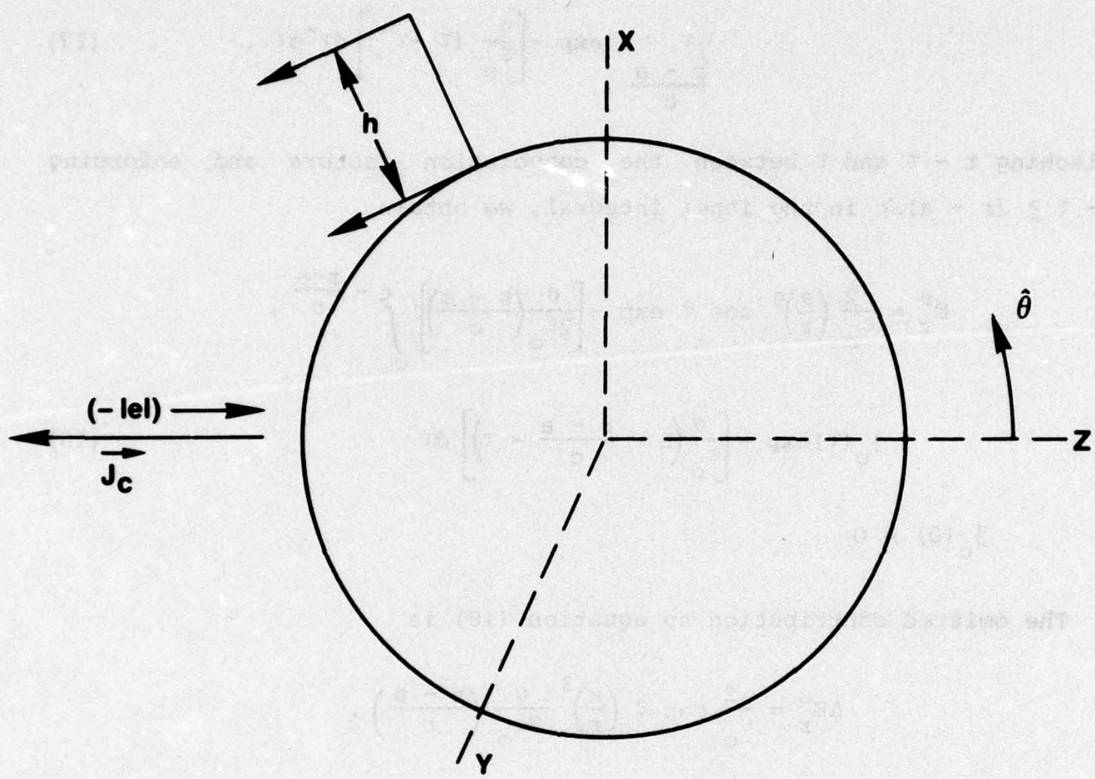

Figure 2. Antenna coupling geometry.

We assume in these calculations that the skin depth in the air is significantly greater than twice the sphere radius. Thus, skin depth is

$$\sim \langle x^2 \rangle^{\frac{1}{2}} = \sqrt{\frac{1.6}{\sigma} \times 10^6 \; t(\text{seconds})} \; (\text{meters}) > 2a \qquad (16)$$

where t is the time of interest.

To use E_r^s for coupling estimates, we shall keep the first term in equation (14) and roughly estimate the importance of the second term. Thus, from equations (12), (14), and (15), we find

$$E_r^s = \frac{2}{\varepsilon_o}\left(\frac{a}{r}\right)^3 \cos\theta \exp\left[-\frac{\sigma}{2\varepsilon_o}\left(\frac{r-a}{c}\right)\right]\int_0^t \frac{\partial j_c(t-\tau)}{\partial(t-\tau)} \cdot$$

$$\int_{\frac{r-a}{c}}^{\tau} \exp -\left[\frac{\sigma}{\varepsilon_o}(\tau-\tau')\right] d\tau' d\tau \ . \qquad (17)$$

Switching $t-\tau$ and τ between the convolution factors and enforcing $t-\tau \geq (r-a)/c$ in the inner integral, we obtain

$$E_r^s = \frac{2}{\varepsilon_o}\left(\frac{a}{r}\right)^3 \cos\theta \exp -\left[\frac{\sigma}{2\varepsilon_o}\left(\frac{r-a}{c}\right)\right] \int_0^{t-\frac{r-a}{c}} \cdot$$

$$j_c(\tau) \exp -\left[\frac{\sigma}{\varepsilon_o}\left(t-\frac{r-a}{c}-\tau\right)\right] d\tau \qquad (18)$$

$$j_c(0) = 0$$

The omitted contribution to equation (18) is

$$\Delta E_r^s = \frac{2}{\varepsilon_o}\cos\theta\left(\frac{a}{r}\right)^3 \frac{\sigma}{2\varepsilon_o}\left(\frac{r-a}{c}\right) \cdot$$

$$\int_0^t j_c'(\tau) \int_{\frac{r-a}{c}}^{t-\tau} \exp -\left[\frac{\sigma}{\varepsilon_o}(t-\tau-\tau')\right] \qquad (19)$$

$$\int_{\frac{r-a}{c}}^{\tau'} \exp -\left(\frac{\sigma}{2\varepsilon_o}\tau''\right) \frac{I_1\left[\frac{\sigma}{2\varepsilon_o}\sqrt{\tau''^2-\left(\frac{r-a}{c}\right)^2}\right]}{\sqrt{\tau''^2-\left(\frac{r-a}{c}\right)^2}} d\tau''$$

$$d\tau' d\tau \ .$$

The τ'' integral in equation (19) is

$$\leq (0.2) \left| \int_1^{\tau'/\left(\frac{r-a}{c}\right)} \frac{\exp\left[-\frac{\sigma}{2\varepsilon_o}\left(\frac{r-a}{c}\right)\left(u - \sqrt{u^2-1}\right)\right]}{\sqrt{u^2-1}} \, du \right.$$

$$\leq (0.2) \int_1^{\tau'/\left(\frac{r-a}{c}\right)} \left(\sqrt{u^2-1}\right)^{-1} du = 0.2 \ln \left[\sqrt{\left(\frac{\tau'}{\left[\frac{r-a}{c}\right]}\right)^2 - 1} + \frac{\tau'}{\left(\frac{r-a}{c}\right)}\right], \quad (20)$$

where the 0.2 comes from a constant approximation (an overestimate) to $e^x I_1(x)$ shown in Abramowitz and Stegun.[2]

Some values of interest are shown in table I.

TABLE I. PARAMETERS FOR THE BESSEL INTEGRAL

u	$u - \sqrt{u^2 - 1}$	$\frac{\tau'}{\left(\frac{r-a}{c}\right)}$	$\ln\left[\sqrt{\frac{\tau'}{\frac{r-a}{c}}^2 - 1} + \frac{\tau'}{\left(\frac{r-a}{c}\right)}\right]$
1	1	1	0
1.5	0.38	5	2.3
3	0.17	10	3.0
5	0.1	100	5.3
10	0.05	1000	7.6

Thus, in the total E_r^s integral, the factor multiplying the exponential in the τ' integration is

$$\leq \left| \left(\exp\left[-\frac{\sigma}{2\varepsilon_o}\left(\frac{r-a}{c}\right)\right] + (0.2) \ln \left[\sqrt{\left(\frac{\tau'}{\left[\frac{r-a}{c}\right]}\right)^2 - 1} + \frac{\tau'}{\left(\frac{r-a}{c}\right)}\right] \frac{\sigma}{2\varepsilon_o}\left(\frac{r-a}{c}\right)\right) \right. \quad (21)$$

[2]*M. Abramowitz and I. A. Stegun, eds., Handbook of Mathematical Functions, National Bureau of Standards, AMS 55 (1965).*

We may use equation (21) to qualitatively judge if the second term from equation (19) is not dominant in our estimate.

The Laplace transform of equation (18) is

$$\tilde{E}_r^s(s) = \frac{2}{\varepsilon_o} \cos\theta \left(\frac{a}{r}\right)^3 \exp -\left[\frac{\sigma}{2\varepsilon_o}\left(\frac{r-a}{c}\right)\right] \exp\left[-\left(\frac{r-a}{c}\right)s\right] \frac{\tilde{j}_c(s)}{\frac{\sigma}{\varepsilon_o} + s} . \quad (22)$$

We shall treat the antenna as a monopole over an infinite, perfectly conducting ground plane. To model the antenna, we use a transmission line analog due to Stark,[4] shown in figure 3. The transmission line is lossless ($\sigma = 0$) and the characteristic impedance is

$$z_c = 60 \left[\ln\left(\frac{2h}{r_o}\right) - 1\right] \text{(ohms)} , \quad (23)$$

where r_o is the antenna radius.

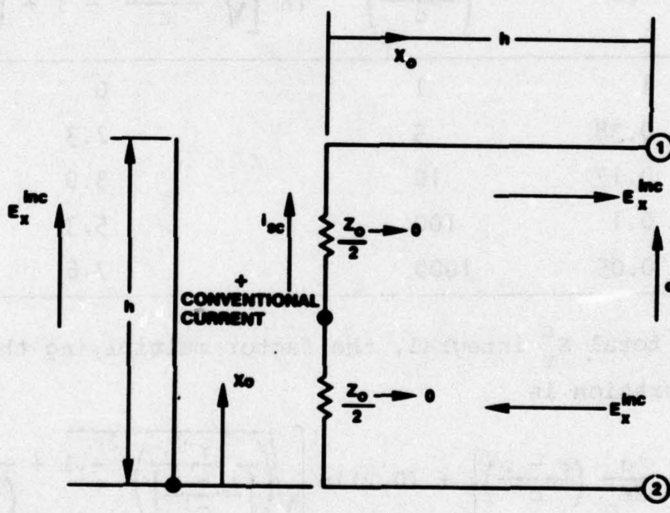

Figure 3. Transmission line antenna model.

[4]*Werner J. Stark, Transient Response of a Log-Periodic Antenna Based on Broad-band Continuous-Wave Measurements, Harry Diamond Laboratories TR-1792 (April 1977).*

The incident field for the transmission line from equation (22)

$$E_{x_o}^{inc}(s) = \frac{2}{\varepsilon_o} \cos\theta \exp\left[-x_o\left(\frac{\alpha}{a} + \frac{\sigma}{2\varepsilon_o c}\right) - x_o \frac{s}{c}\right] \cdot \frac{j_c(s)}{s + \frac{\sigma}{\varepsilon_o}} \tag{24}$$

where we have approximated the $\left(\frac{a}{r}\right)^3$ falloff by an exponential as shown typically in table II.

TABLE II. EXPONENTIAL APPROXIMATION TO $\left(\frac{a}{r}\right)^3$: (a = 1 m)

r	$\left(\frac{a}{r}\right)^3$	$\exp\left[-\frac{\alpha}{a}(r-a)\right]$		
		$\frac{\alpha}{a} = 2.08$	$\frac{\alpha}{a} = 1.5$	$\frac{\alpha}{a} = 1$
a	1.0	1.0	1.0	1.0
1.25a	0.51	0.59	0.69	0.78
1.5a	0.30	0.35	0.47	0.61
2.0a	0.13	0.12	0.22	0.37

In comparison, $\frac{\sigma}{2\varepsilon_o c} = 0.02 \frac{\sigma}{10^{-4}}$.

The transmission line response (see sect. 6) to

$$E_{step}^{inc} = \frac{1}{s} \exp\left(-\frac{x_o s}{c}\right) \exp\left[-x_o\left(\frac{\alpha}{a} + \frac{\sigma}{2\varepsilon_o c}\right)\right] \tag{25}$$

is shown in figure 4.

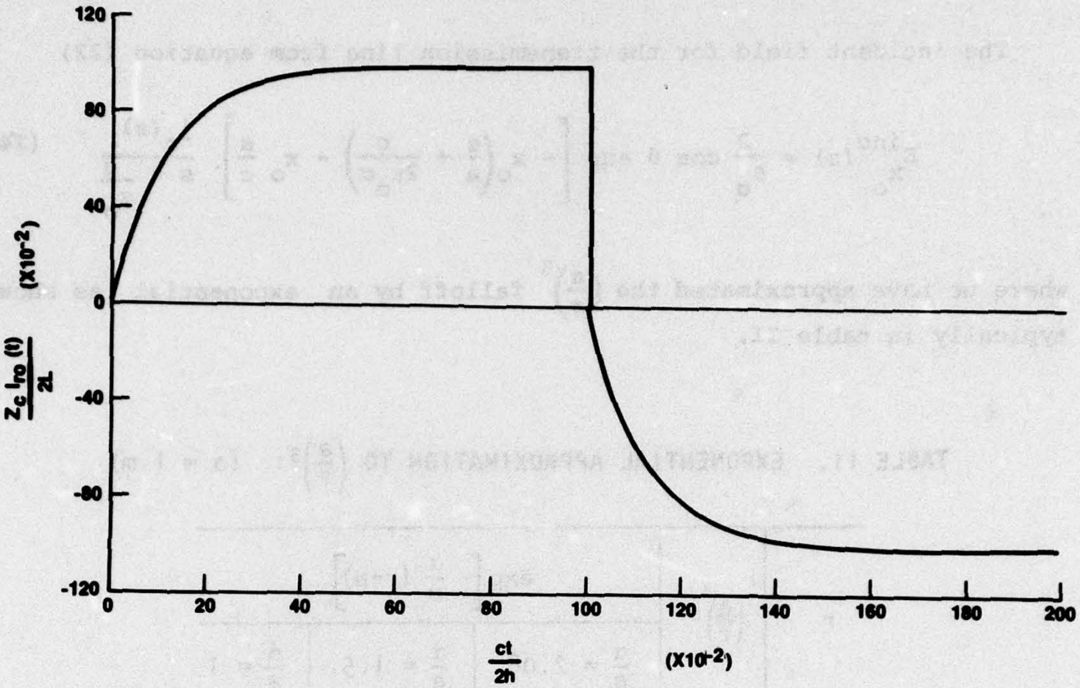

Figure 4. Transmission line response $I_{ro}(t)$ to equation (25): $\sigma = o$, L from equation (31), $1\frac{V}{M}$.

From equation (25) we may then convolve $I_{ro}(t)$ with $e^{-\sigma/\varepsilon_o t}$ and restore the amplitude:

$$I_r(t) = \frac{2}{\varepsilon_o} \cos\theta \int_o^t I_{ro}(t - \tau)\exp\left(-\frac{\sigma}{\varepsilon_o}\tau\right) d\tau$$

$$= \frac{2L}{z_c}\left[\frac{1 - \exp\left(-\frac{\sigma}{\varepsilon_o}t\right)}{\frac{\sigma}{\varepsilon_o}} - \frac{\exp\left(-\frac{\sigma}{\varepsilon_o}t\right) - \exp\left(-\frac{c}{2L}t\right)}{\frac{c}{2L} - \frac{\sigma}{\varepsilon_o}}\right], \quad 0 \leq t \leq \frac{2h}{c} = t_1$$

$$= \frac{2L}{z_c}\left[\frac{\exp\left[-\frac{\sigma}{\varepsilon_o}(t - t_1)\right] - 1}{\frac{\sigma}{\varepsilon_o}} + \frac{\exp\left[-\frac{\sigma}{\varepsilon_o}(t - t_1)\right] - \exp -\left(\frac{\sigma}{\varepsilon_o}t\right)}{\frac{\sigma}{\varepsilon_o}}\right.$$

$$+\frac{\exp\left[-\frac{\sigma}{\varepsilon_o}(t - t_1)\right] - \exp\left[-\frac{c}{2L}(t - t_1)\right]}{\frac{c}{2L} - \frac{\sigma}{\varepsilon_o}}$$

$$\left. - \frac{\exp\left[-\frac{\sigma}{\varepsilon_o} t\right] - \exp\left[-\frac{\sigma}{\varepsilon_o}(t - t_1)\right] \exp\left(-\frac{c}{2L} t_1\right)}{\frac{c}{2L} - \frac{\sigma}{\varepsilon_o}} \right] , \quad t_1 \le t \le 2t_1 \ . \tag{26}$$

The constant L is given in equation (31) below. The short-circuit current estimate is

$$I_{sc}(t) = \int_0^t \frac{\partial}{\partial(t - \tau)} \left[j_c(t - \tau)u(t - \tau)\right] \ I_r(\tau) \ d\tau \tag{27}$$

where the voltage and current polarities (see fig. 3) are

$$V_{line} = -\int_2^1 \vec{E}_l \cdot \vec{d}_l$$

$$\frac{\partial V}{\partial x} = -L_o \frac{\partial i_1}{\partial t} + E_x^{i^1} - E_x^{i^2} \ , \tag{28}$$

where L_o is line inductance per unit length. Equation (27) has a Laplace transform identical to the more familiar form in which $j_c \rightarrow E^s$, $I_r \rightarrow I_{ro}$. Uniqueness is again assured by Lerch's Theorem.

We choose the following test pulse, shown in figure 5,

$$j_c(t) = \frac{j_m}{t_r} \ t \ \exp\left(1 - \frac{t}{t_r}\right) A/m^2 \ . \tag{29}$$

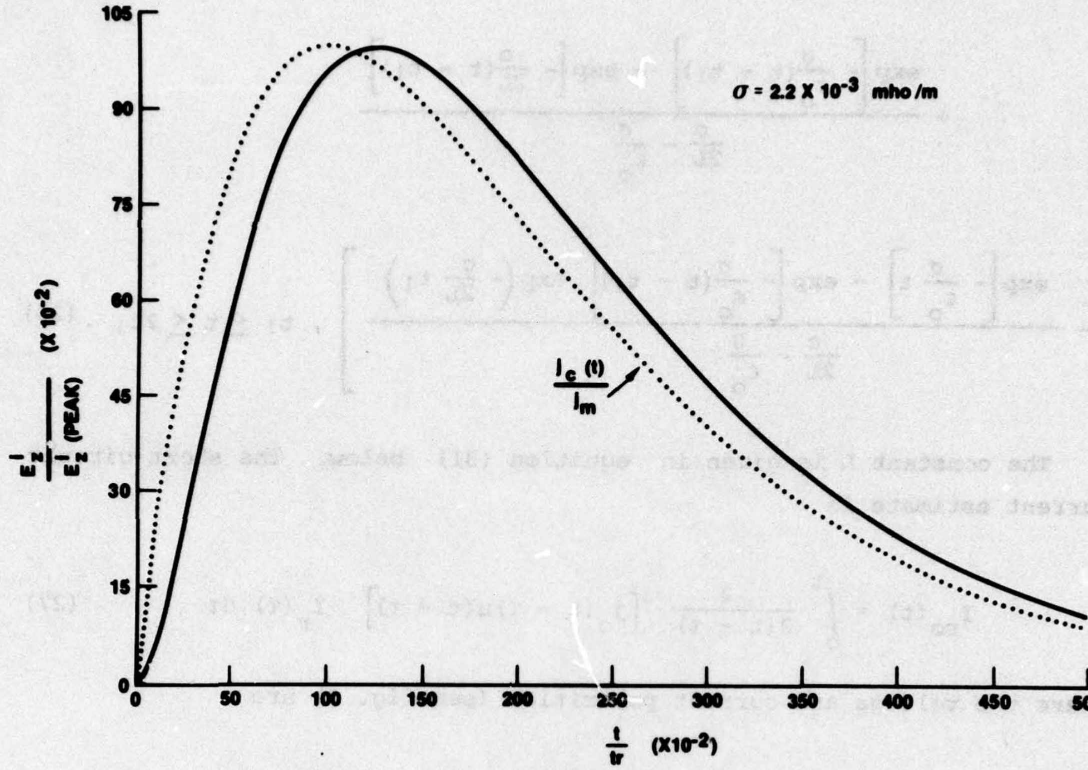

Figure 5. Incident electric field E_z^i and Compton current pulse.

From equations (26) and (27) (see sect. 6, eq 59),

$$I_{sc}\left(0 \le t \le t_1 = \frac{2h}{c}\right) = \frac{2}{\varepsilon_o} \cos\theta \left(\frac{2L}{z_c}\right) j_m t_r \, e^1 \, \frac{\frac{c}{2L}}{\frac{c}{2L} - \frac{\sigma}{\varepsilon_o}} \cdot$$

$$\left[\frac{t}{t_r} \exp\left(-\frac{t}{t_r}\right) \frac{\frac{c}{2L} t_r - \frac{\sigma}{\varepsilon_o} t_r}{\left(\frac{\sigma}{\varepsilon_o} t_r - 1\right)\left(\frac{c}{2L} t_r - 1\right)} + \frac{1}{\left(\frac{c}{2L} t_r - 1\right)^2} \cdot\right.$$

$$\left.\left(\exp\left[-\frac{t}{t_r}\right] - \exp\left[-\frac{c}{2L} t\right]\right) + \frac{1}{\left(\frac{\sigma}{\varepsilon_o} t_r - 1\right)^2} \left(\exp\left[-\frac{\sigma}{\varepsilon_o} t\right] - \exp\left[-\frac{t}{t_r}\right]\right)\right] \quad (30)$$

where

$$L = \frac{1}{\frac{\alpha}{a} + \frac{\sigma}{2\varepsilon_o c}} \text{ (see table II)} , \tag{31}$$

$$I_{sc}\left(t_1 \le t \le \frac{4h}{c}\right) = \frac{2}{\varepsilon_o} \cos\theta \left(\frac{2L}{z_c}\right) j_m t_r e^1 \left\{\left[-2 + \exp -\left(\frac{\sigma}{\varepsilon_o} t_1\right)\right.\right.$$

$$\left.+ \frac{\frac{\sigma}{\varepsilon_o}}{\frac{c}{2L} - \frac{\sigma}{\varepsilon_o}} \left(\exp\left[-\frac{\sigma}{\varepsilon_o} t_1\right] - 1 - \exp\left[-\frac{c}{2L} t_1\right]\right)\right] \left[\frac{\left(\frac{t - t_1}{t_r}\right)\exp\left(-\frac{t - t_1}{t_r}\right)}{\frac{\sigma}{\varepsilon_o} t_r - 1}\right.$$

$$\left. - \frac{1}{\left(\frac{\sigma}{\varepsilon_o} t_r - 1\right)^2} \left(\exp\left[-\frac{t - t_1}{t_r}\right] - \exp\left[-\frac{\sigma}{\varepsilon_o}(t - t_1)\right]\right)\right]$$

$$+ \frac{\frac{c}{2L}}{\frac{c}{2L} - \frac{\sigma}{\varepsilon_o}} \left[\frac{\left(\frac{t - t_1}{t_r}\right)\exp\left(-\frac{t - t_1}{t_r}\right)}{\frac{c}{2L} t_r - 1}\right.$$

$$\left. - \frac{1}{\left(\frac{c}{2L} t_r - 1\right)^2} \left(\exp\left[-\frac{t - t_1}{t_r}\right] - \exp\left[-\frac{c}{2L}(t - t_1)\right]\right)\right]$$

$$+ \frac{\frac{c}{2L}}{\frac{c}{2L} - \frac{\sigma}{\varepsilon_o}} \left[\left(\frac{t}{t_r}\right)\exp\left(-\frac{t}{t_r}\right) \frac{\frac{c}{2L} t_r - \frac{\sigma}{\varepsilon_o} t_r}{\left(\frac{c}{2L} t_r - 1\right)\left(\frac{\sigma}{\varepsilon_o} t_r - 1\right)}\right.$$

$$+ \frac{1}{\left(\frac{c}{2L} t_r - 1\right)^2} \left(\exp\left[-\frac{t}{t_r}\right] - \exp\left[-\frac{t - t_1}{t_r}\right] \exp\left[-\frac{ct_1}{2L}\right]\right)$$

$$+ \frac{1}{\left(\frac{\sigma}{\varepsilon_o} t_r - 1\right)^2} \left(\exp\left[- \frac{t - t_1}{t_r} \right] \exp\left[- \frac{\sigma}{\varepsilon_o} t_1 \right] - \exp\left[- \frac{t}{t_r} \right] \right)$$

$$+ \left(\frac{t - t_1}{t_r} \right) \exp\left(- \frac{t - t_1}{t_r} \right) \left(\frac{\exp\left[- \frac{c}{2L} t_1 \right]}{\frac{c}{2L} t_r - 1} - \frac{\exp\left[- \frac{\sigma}{\varepsilon_o} t_1 \right]}{\frac{\sigma}{\varepsilon_o} t_r - 1} \right) \Bigg] \Bigg\} \tag{32}$$

Equations (30) and (32) are only valid for the following restriction since only $I_{ro}(t)$ was so simplified.

$$\exp\left(- \frac{h}{L} \right) << 1 \ . \tag{33}$$

4. SAMPLE CALCULATION

If we use the model of section 3 for a sphere near a ground plane, we should attempt to take some account of E^i in the presence of the ground. Following a suggestion of Bombardt, we force E^i by adjusting j_m, t_r, and σ to be as representative as possible of some prescribed near-ground horizontal electric field.

Now,

$$\varepsilon_o \dot{E}_z^i + \sigma E_z^i = -J_c \tag{34}$$

and with our test pulse,

$$E_z^i = \frac{j_m e^1 t_r}{\varepsilon_o} \left[\frac{\left(\frac{t}{t_r}\right) \exp\left(- \frac{t}{t_r} \right)}{\frac{\sigma}{\varepsilon_o} t_r - 1} + \frac{\exp\left[- \frac{\sigma}{\varepsilon_o} t_r \left(\frac{t}{t_r} \right) \right] - \exp\left(- \frac{t}{t_r} \right)}{\left(\frac{\sigma}{\varepsilon_o} t_r - 1 \right)^2} \right] . \tag{35}$$

This electric field peaks at

$$\left(\frac{t}{t_r}\right)_{peak} = \frac{\left(\frac{\sigma}{\varepsilon_o} t_r\right)\left[1 - \exp\left(-\left(\frac{\sigma}{\varepsilon_o} t_r - 1\right)\left(\frac{t}{t_r}\right)_{peak}\right)\right]}{\frac{\sigma}{\varepsilon_o} t_r - 1} . \tag{36}$$

In order to have a peak, we must fix t_r and select $\left(\sigma/\varepsilon_o\right)t_r > 1$. For the example, we choose

$z_c = 372$ ohms,

$a = 1$ m,

$\frac{\alpha}{a} = 2.08$ (table II),

$h = 4$ m, and

$t_r = 20$ ns,

in which case the exponential more closely approximates $\left(\frac{a}{r}\right)^3$. The electric field E_z^i at $r=a$ for one value of $\left(\sigma/\varepsilon_o\right)t_r$ is shown in figure 5. The short-circuit current estimate for the case in figure 5 is shown in figure 6.

The peak value of I_{sc} is

$$\left|I_{sc}\right| \text{(first peak)} \sim (1.9) j_m(1) \left|\cos \theta\right| \tag{37}$$

$$\left(\frac{\sigma}{\varepsilon_o} t_r = 5\right) . \tag{38}$$

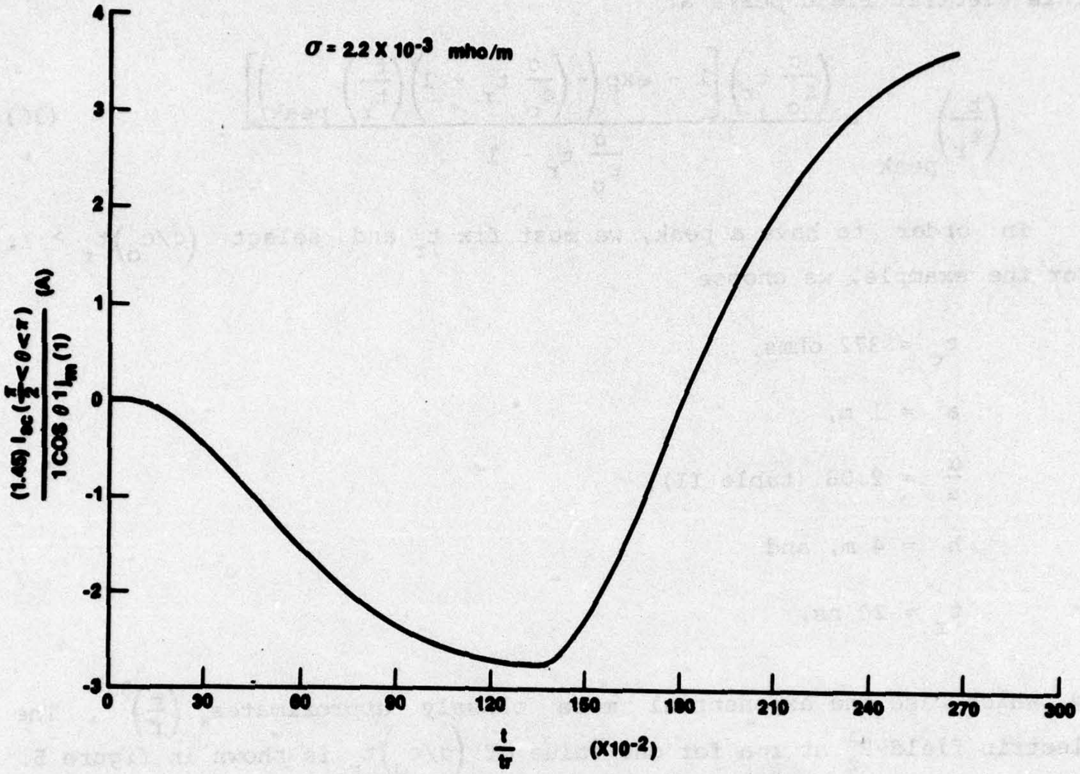

Figure 6. Short-circuit current ($\frac{\alpha}{a}$ = 2.08).

Let us now vary the exponential attenuation, $\frac{\alpha}{a}$, while keeping the remaining parameter set fixed. Results are shown in figures 7 and 8. The peak currents vary monotonically upward as the attenuation is decreased.

The ideally gamma-thin sphere model[1] yields a net time-dependent charge which is equal to the total charge that would be present in the volume of conducting medium excluded by the sphere. Our approximate driving electric field E_r^s yields zero net charge on the sphere.

---

[1]*J. N. Bombardt, Jr., Electromagnetic Response of a Sphere Over a Ground Plane in the Presence of Source and Conduction Currents in the Air, Harry Diamond Laboratories TR-1716 (October 1975).*

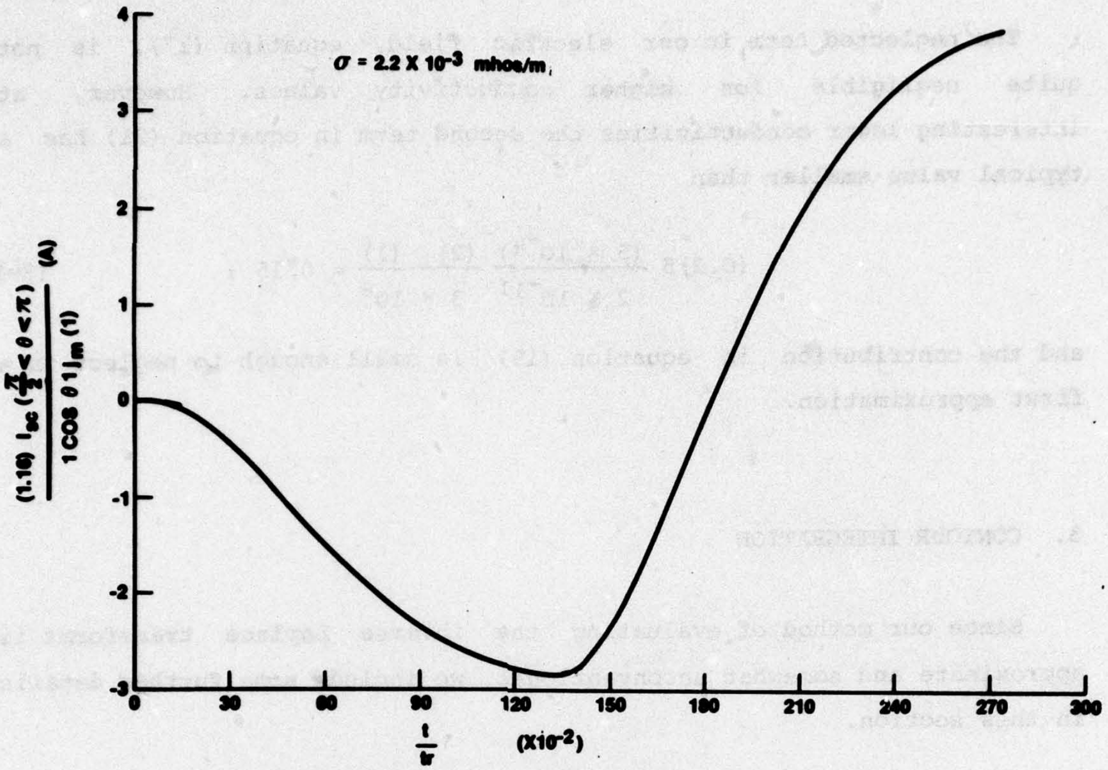

Figure 7. Short-circuit current ($\alpha/a = 1.5$).

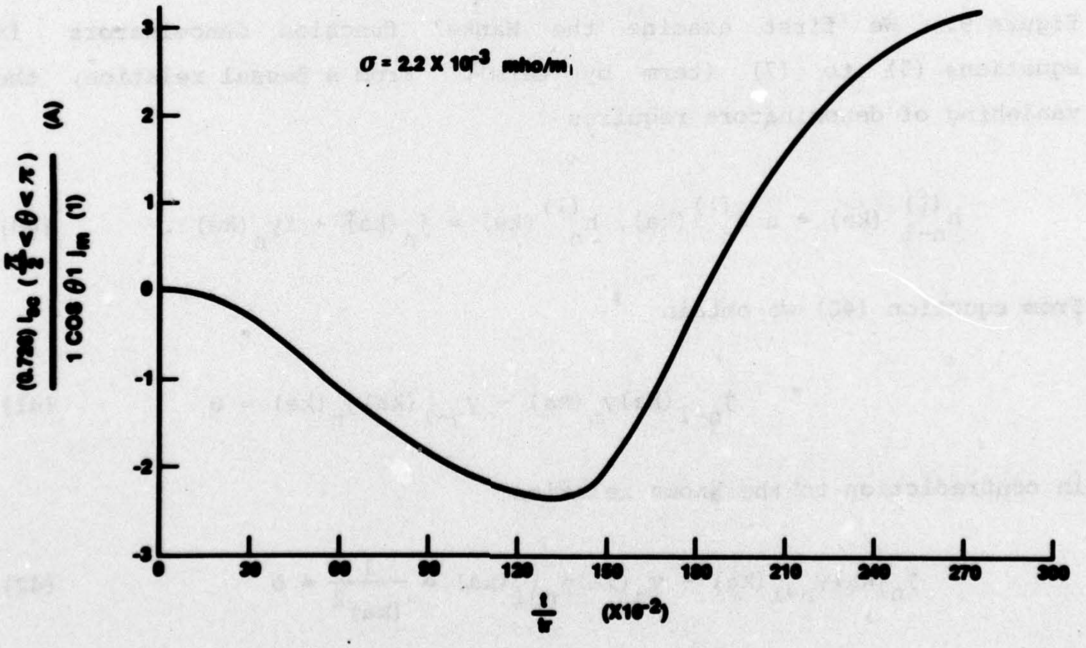

Figure 8. Short-circuit current ($\alpha/a = 1.0$).

The neglected term in our electric field, equation (17), is not quite negligible for higher conductivity values. However, at interesting lower conductivities the second term in equation (21) has a typical value smaller than

$$(0.2)5 \frac{(5 \times 10^{-4})}{2 \times 10^{-11}} \frac{(2) \quad (1)}{3 \times 10^{8}} = 0.15 \; ; \tag{39}$$

and the contribution in equation (19) is small enough to neglect in a first approximation.

5. CONTOUR INTEGRATION

Since our method of evaluating the inverse Laplace transforms is approximate and somewhat unconventional, we include some further details in this section.

The Bromwich contour for evaluation of equation (9) is shown in figure 9. We first examine the Hankel function denominators in equations (5) to (7) (term by term). From a Bessel relation, the vanishing of denominators requires

$$h_{n-1}^{(1)}(ka) = n\, h_n^{(1)}(ka), \; h_n^{(1)}(ka) = j_n(ka) + iy_n(ka) \; . \tag{40}$$

From equation (40) we obtain

$$j_{n-1}(ka)y_n(ka) - y_{n-1}(ka)j_n(ka) = 0 \tag{41}$$

in contradiction to the known relation

$$j_n(ka)y_{n-1}(ka) - y_n(ka)j_{n-1}(ka) = \frac{1}{(ka)^2} \neq 0 \tag{42}$$

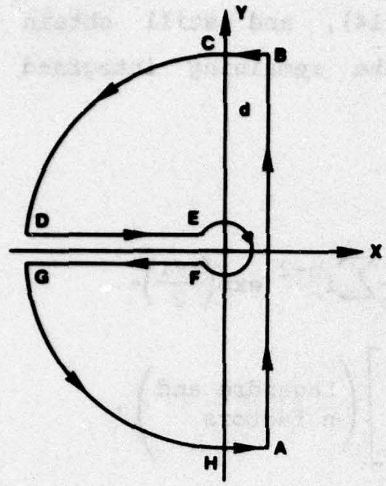

Figure 9. Bromwich contour.

since $\sigma \neq 0$. As $|k| \to 0$, the Hankel function factors in our residue evaluations vanish. For convenience we work with the Laplace variable

$$s = d - i\omega\,. \tag{43}$$

The argument of the Hankel functions comes from

$$k^2 = i\omega\mu_o(\sigma - i\omega\varepsilon_o)$$

$$k = \frac{1}{c}\, e^{i\pi/4} k_o \exp\left[i\left(\frac{\theta_o}{2} + m\pi\right)\right] \tag{44}$$

$$m = 0, \pm 1, \pm 2, \ldots$$

where

$$z = r_o e^{i\theta} \tag{45}$$

$$k_o = \frac{\sqrt{r_o}}{c}\left[r_o^2 + 2\,\frac{\sigma}{\varepsilon_o}\, r_o \cos\theta + \left(\frac{\sigma}{\varepsilon_o}\right)^2\right]^{1/4} \tag{46}$$

$$\theta_o = \text{arc tan}\left[\frac{r_o \sin 2\theta + \dfrac{\sigma}{\varepsilon_o}\sin\theta}{r_o \cos 2\theta + \dfrac{\sigma}{\varepsilon_o}\cos\theta}\right] + \ell\pi \tag{47}$$

$$\ell = 0, \pm 1, \pm 2, \ldots$$

First we state that (term by term) the modulus of $\exp\,(a/v)z\ \tilde{g}(z)$ vanishes on CB and HA where $\tilde{g}(z)$ are the integrands resulting from the fields in equations (5) to (7). The integrand moduli also vanish on AB as $r_o \to \infty$.

Likewise, the integrand moduli also vanish on CD and GH as $r_o \to \infty$. We find that we may remove as a convolution factor:

$$\frac{\exp\left[ik(r-a)\right]}{z} \to \frac{\exp\left[-\left(\dfrac{r-a}{c}\right)\sqrt{s\left(s + \dfrac{\sigma}{\varepsilon_o}\right)}\right]}{s} \tag{48}$$

the known transform of which[5] yields equation (14), and still obtain vanishing moduli on the contour extremes for the remaining integrand factors.

The loop integrals DEFG are of the form

$$I_{loop} = -\int_0^\infty dx\, e^{-tx} \exp\left(-\frac{a}{v}x\right)\left(\begin{matrix}\text{numerical}\\ \text{factor}\end{matrix}\right)\frac{1}{x}\sum i^{n-2} \exp\left(\frac{n\pi i}{2}\right) \cdot$$

$$\frac{-\left(\frac{a}{v}x\right)^n}{1.3..(2n+1)}\left[1 + \frac{\frac{\left(\frac{a}{v}x\right)^2}{2}}{(2n+3)} + \ldots\right]\left(\begin{matrix}\text{Legendre and}\\ \text{n factors}\end{matrix}\right) \cdot$$

$$\left[F_H\left(|x|e^{-\pi i}\right) - F_H\left(|x|e^{\pi i}\right)\right] e^{dt} \tag{49}$$

where F_H is a Hankel function factor--the exponential in the Hankel products is in the convolution product of equation (48). We find that the small circle integral vanishes as $\rho \to 0$ because of the ρ factor from dz in $z = \rho e^{i\theta}$ on the circle. We find explicitly that the difference of the functions F_H in equation (50) is always zero (even for $|k| = 0$); hence, the loop integrals contribute nothing within our approximate problem formulation.

The residue evaluation for H_ϕ including the ansatz is

$$\operatorname{Res}\left(\tilde{H}_\phi(z)\frac{1}{z+\varepsilon}\right)_{(48)\text{ removed}} = a\left(\frac{a}{r}\right)^2 \sin\theta \exp\left[-\varepsilon\left(t + \frac{a}{v}\right)\right] e^{dt} \tag{50}$$

For ε and d infinitesimal, we differentiate equation (50) to obtain

$$\simeq a\left(\frac{a}{r}\right)^2 \sin\theta\,\delta\,(t)\ . \tag{51}$$

Equation (51) convolved with equation (14) yields equation (11).

---

[5] *N. W. McLachlan, Complex Variable Theory and Transform Calculus, Cambridge (1963).*

Using the pole at $z_o = -\frac{\sigma}{\varepsilon_o}$, the residue evaluations for the electric fields yield

$$\simeq \frac{1}{\varepsilon_o}\left(\frac{a}{r}\right)^3 \sin\theta \exp\left(-\frac{\sigma}{\varepsilon_o}t\right) : (E_\theta) \tag{52}$$

$$\simeq \frac{2}{\varepsilon_o}\left(\frac{a}{r}\right)^3 \cos\theta \exp\left(-\frac{\sigma}{\varepsilon_o}t\right) : (E_r) \tag{53}$$

Convolving equations (52) and (53) with (14) yields (13) and (12), respectively.

Utilizing the δ function ansatz, the electric field evaluation yields equation (15) with $j_c \to$ (35) and $g^{step} \to \left(\frac{a}{r}\right)^3 \sin\theta D(\tau)$, $2\left(\frac{a}{r}\right)^2 \cos\theta D(\tau)$ for E_θ, E_r, respectively.

6. TRANSMISSION LINE

The transmission line solution in sections 3 and 4 is straightforward. We include the following development for completeness.

The Laplace-domain short-circuit current for the (lossless) transmission line of figure 3 ($x_o \to$ is the space variable increasing toward the open end) is

$$\tilde{I}_{ro}(s) = \frac{2}{z_c}\frac{1}{1+\exp\left(-\frac{2sh}{c}\right)}\int_0^h dx_o\, \tilde{E}^{inc}_{x_o}(x_o,s) \left[\exp\left(-\frac{sx_o}{c}\right) - \exp\left(-\frac{s}{c}\left[2h - x_o\right]\right)\right] \tag{54}$$

where, for a step

$$\tilde{E}^{inc}_{x_o}(x_o,s) = \exp\left(-\frac{\alpha}{a}x_o\right)\exp\left(-\frac{x_o s}{c}\right)\left(\frac{1}{s}\right). \tag{55}$$

From a series development of equation (54) we find

$$I_{ro}(t) = I_1(t) + I_2(t) + I_3(t) \tag{56}$$

where

$$I_1(t) = \frac{2a}{\alpha z_c}\left[1 - \exp\left(-\frac{c\alpha}{2a}\,t\right)\right] \quad 0 \le t \le \frac{2h}{c}$$

$$= \left(\frac{2a}{\alpha z_c}\right)\left[1 - \exp\left(-\frac{\alpha h}{a}\right)\right] \exp\left[-\frac{c\alpha}{2a}\left(t - \frac{2h}{c}\right)\right]\left(\frac{2h}{c} \le t \le \frac{4h}{c}\right), \tag{57}$$

and we are interested only in the case

$$\exp\left(-\frac{\alpha h}{a}\right) << 1 . \tag{58}$$

Now,

$$I_2(t) = -\exp\left(-\frac{\alpha h}{a}\right) I_1\left(t - \frac{2h}{c}\right) u\left(t - \frac{2h}{c}\right) \tag{59}$$

and

$$I_3(t) = -\frac{2a}{\alpha z_c}\left[1 - \exp\left(-\frac{\alpha h}{a}\right)\right]\left[\overline{\frac{2h}{c} \quad \frac{4h}{c}}\,,\ \overline{\frac{6h}{c} \quad \frac{8h}{c}}\,, \ldots\right] .$$

Assuming equation (58), the response (56) is shown in figure 4.

7. CONCLUDING REMARKS

The radial scattered electric field solution obtained in section 3 should be used strictly in an essentially quasistatic situation. It appears, however, that only an exact analytic solution for the Compton-driven sphere in a dissipative medium will provide a satisfying resolution of this problem.

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